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DESIGN, DEVELOPMENT, AND FABRICATION OF A PROTOTYPE HIGH-VOLUME PARTICULATE MASS SAMPLING TRAIN

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Acurex Corporation

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The report gives results of a program to develop a high-volume sampling train with the following characteristics: 5-10 cfm sampling rate, modular, portable, 500 F probe/oven temperature, and conforming to Federal Register Method 5 basic requirements (standards of performance for new stationary sources). The program included a study of the overall requirements of stack sampling instrumentation, concluding with recommendations for portable, easier to use systems that are effective over a wide range of sampling rates.

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The principal individuals involved at Aerotherm were Dr. W. F. Lapson, Project Manager, Mr. Hans-Joachim Dehne, Project Engineer, and Mr. Richard Beer, Designer. Appreciation is also acknowledged for those who participated in the conception of the project; Mr. Ken Lambson, Mr. Nick Davis, and Dr. Larry Anderson.

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SECTION 1

INTRODUCTION

Currently available particulate mass sampling systems typically sample at rates less than 1 cfm. One consequence of this low sampling rate is an excessively long sampling period during which plant operating conditions may vary widely.

Another shortcoming of most sampling trains is that the temperature of the probe and filter oven is usually less than 300°F. This permits condensation of such vapors as sulfur trioxide which interferes with the determination of particulate concentration.

The Control Systems Laboratory of the EPA has been using a high volume (approximately 7 cfm) version of a Federal Register, Method 5 particulate sampling train for several years. This sampling train was bulky, difficult to transport, and in many respects lacked the refinement of a commercial product. The Control Systems Laboratory therefore sponsored a program for the development of a high volume sampling train having the following features:

- Sampling rate of 5-10 cfm
- Modular assembly
- Portability
- Probe and oven temperatures up to 500°F
- Conformance to basic requirements of Method 5, Standards of Performance for New Stationary Sources, Federal Register (December 23, 1971), Volume 36, No. 247.

Aerotherm has delivered two high volume sampler trains to the EPA satisfying the above requirements. The new samplers are not much larger than the common samplers operating at 1 cfm.

One of the objectives of this program was to study the overall requirements of stack sampling instrumentation. The study concludes with recommendations for sampling systems which are more portable, easier to use, and effective over a wide range of sampling rates. It appears that the greatest advance in sampling trains will result from automation based on the use of a small, dedicated digital computer. The flowrate adjustments for isokinetic conditions would be established by this computer. In an automated system, all of the parameters important to the

stack sampling procedure would exist as electrical signals and therefore can be recorded easily. By relying on electronic rather than mechanical instrumentation, many bulky components can be eliminated, thus resulting in a lighter system. One of the most important advantages of the automated sampler would be its capability for rapidly adjusting to changes in stack velocity or temperature. This is especially important when sampling at high flowrates.

SECTION 2

REVIEW OF THE DEVELOPMENT OF A PROTOTYPE HIGH-VOLUME PARTICULATE MASS SAMPLING TRAIN

The high volume sampling train delivered to the EPA samples at nearly ten times the rate of ordinary sampling systems while remaining nearly as compact (Figure 2-1). The system is very rugged. The principal features are summarized below:

- Sampling rates up to 6 cfm
- Oven and probe temperatures up to 500°F
- System breaks down into easily carried modules
- Fiberglass, cushioned cases for carrying and shipment of each piece of equipment
- Oil-less vane pump modified for low leakage
- Two Magnehelic gages for accurate readout over the pitot tube range of 0-4 inches of water
- Round probe body for ease in sealing the sampling port
- Probe can be rotated for sampling horizontal ducts located at same level or below the sampling train
- Impinger train and ice bath separable from oven
- All glassware eliminated to avoid breakage problems - stainless steel, Lexan, or teflon are used instead of glass
- Enlarged impinger bottles with demisters to prevent water carry-over at flowrates up to 8 cfm
- Stable uni-rail traversing stand for guiding probe in horizontal or vertical directions
- Circuit breakers instead of fuses
- Separate power lines for heaters and pump to assure obtainability of required power.

In the following discussion, the sampling train will be described in greater detail with comments regarding the basis of design decisions.

2.1 CONTROL UNIT

The control unit contains all of the instruments required for measuring stack velocity, sampling flowrate and cumulative flow, and temperatures at various points in the sampling system (Figure 2-2). All of the controls for the sampling system are located in the control unit with the exception of the valves for controlling sample flowrate. The valves are mounted on the vacuum pump, which is placed adjacent to the control unit when using the sampling system. Thus all of the controls and measurement displays are centered about the control unit.

Each of the items seen on the face of the control unit are described below.

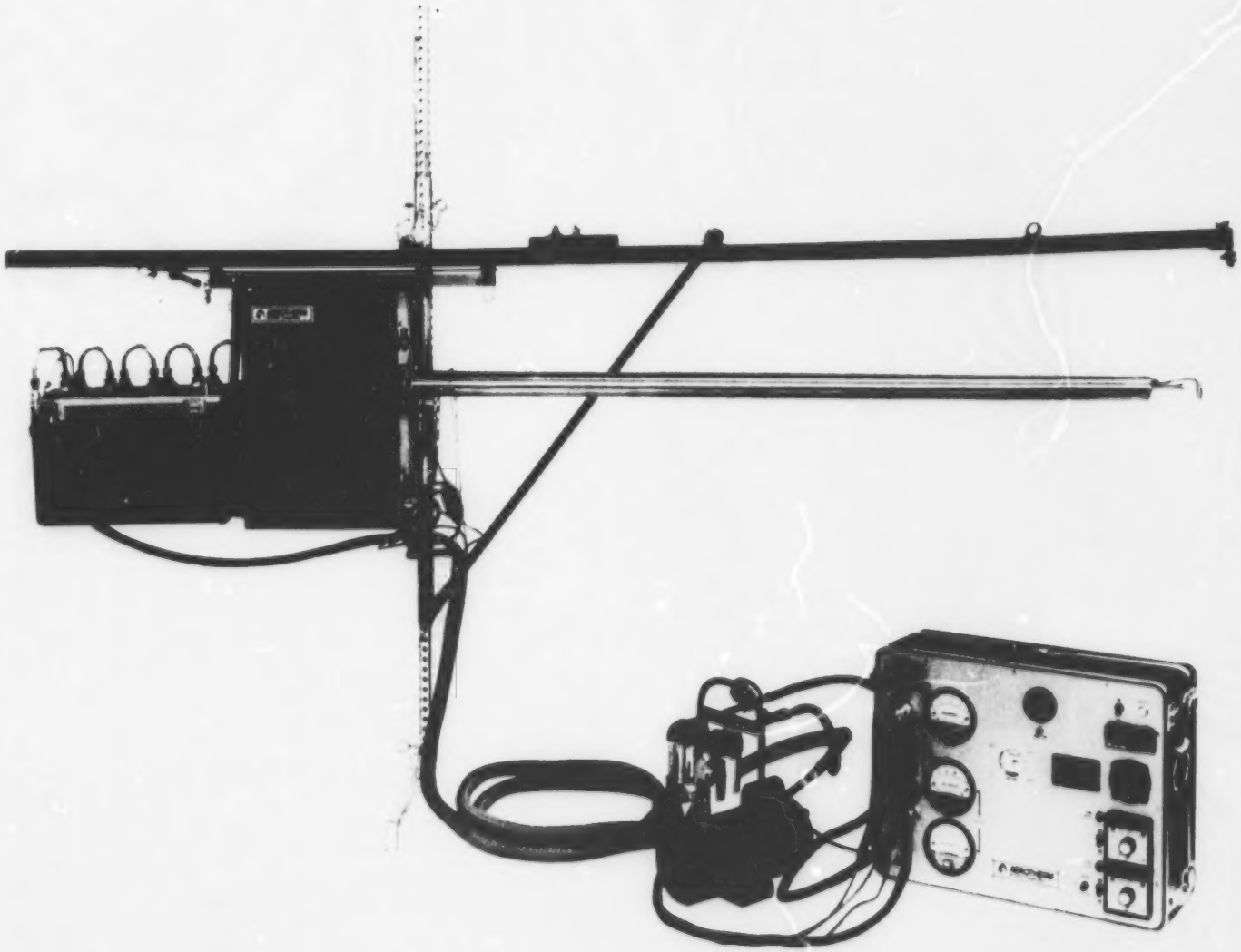


Figure 2-1. High Volume Particulate Sampling Train

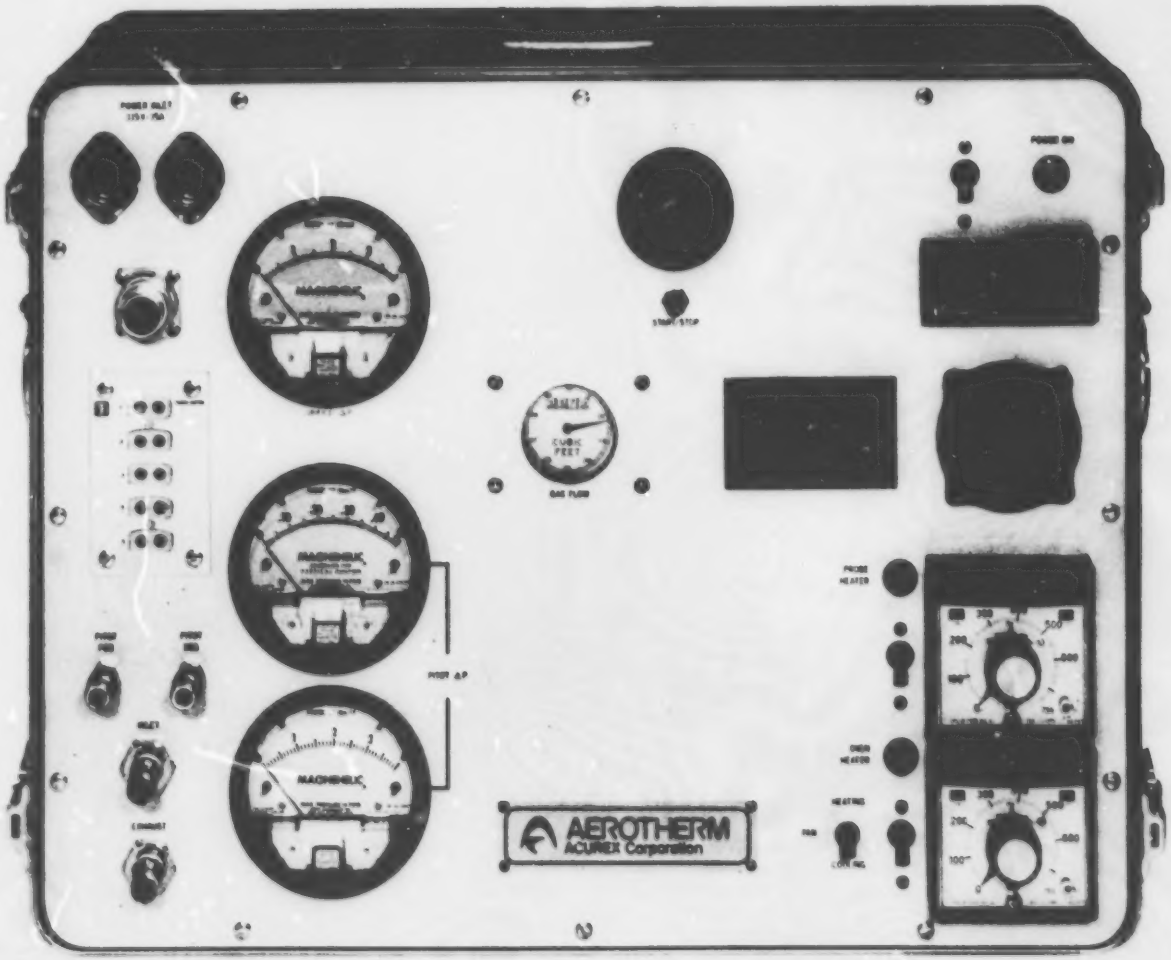


Figure 2-2. Control Unit

Switches

There are five electrical switches with the following functions:

- Main power (with pilot light and circuit breaker)
- Probe heater (with pilot light and circuit breaker)
- Oven heater (with pilot light and circuit breaker)
- Fan power
- Elapsed time indicator start/stop switch

Circuit breakers have been used instead of fuses to avoid the problem of running short of fuses. The oven circulation fan has been connected so that during heating the fan is in operation regardless of the position of the fan control switch. When the oven heater is "off", the fan may be turned "on" with the oven door open to hasten cooling of the oven, cyclone, and filter.

Elapsed Time Indicator

An elapsed time indicator is used to determine when to move from one traverse point to the next. The indicator has a resolution of one-hundredth of a minute. The indicator can be re-set to zero, and started or stopped with pushbuttons located near the indicator.

Oven and Probe Heater Temperature Controls

Power to the oven and probe heating elements is modulated with adjustable temperature controllers. These controllers use thermocouples for temperature sensing. Each controller has the following features:

- Actual temperature continuously displayed
- Maximum set-point is limited to 500°F by a mechanical stop
- Power "on" or "off" is indicated by red and green lights.

Some sampling trains use oven and probe heater controls located at the oven. Frequently these controls are only simple adjustments to the input power and do not involve any thermostatic control. The oven and probe heater controls were located on the control unit because under some conditions the oven is inaccessible for adjustment. This occurs while sampling large stacks when the oven may be located beyond the edge of the sampling platform. Feedback control of the temperature is used because the ambient conditions under which stack sampling is performed are highly variable. The concern for accurate temperature control is based on the fact that many of the effluents sampled have condensible components. These components, e.g., water and sulfur trioxide, must be maintained as vapor prior to filtering out the particulates.

The actual switching of power to the heating elements in the probe and oven is done by heavy duty relays (lower right corner, Figure 2-3). This greatly increases the capacity for the system to use longer probes or hotter ovens, both requiring greater power.

Temperature Display

A digital temperature indicator is used together with an eight-point selector switch. The selector switch permits monitoring the temperature by means of thermocouples at each of the following locations:

- Stack
- Probe
- Oven
- Impinger train outlet
- Gas meter outlet
- Gas meter inlet
- Two "spare" locations.

The temperature range is 0° to 2000°F with an accuracy of ± 4°F.

Gas Flow

The cumulative sample gas flow is measured by a Rockwell Model 415 gas meter. This is a high accuracy meter used for testing purposes. The measurement is displayed by a digital counter and pointer with a resolution of 0.005 ft^3.

Pressure Gages

Three Magnehelic pressure gages can be seen on the face of the control unit. One is used for monitoring the pressure drop across the orifice meter (see discussion on orifice meter below). The other two gages are connected in parallel and indicate the pressure differential of the pitot tube used for measuring stack velocity. One of the gages has a range from 0 to 0 5 inches of water, the other, 0 to 4 inches of water. Thus the pitot tube pressure differential can be determined with high accuracy over the full range of 0 to 4 inches of water.

Instead of Magnehelic gages, inclined/vertical manometers were considered. This type of manometer has increased resolution at low pressures, the same as the two-gage system described above. Manometers are often used as a primary standard and the readings obtained with them are usually trustworthy in

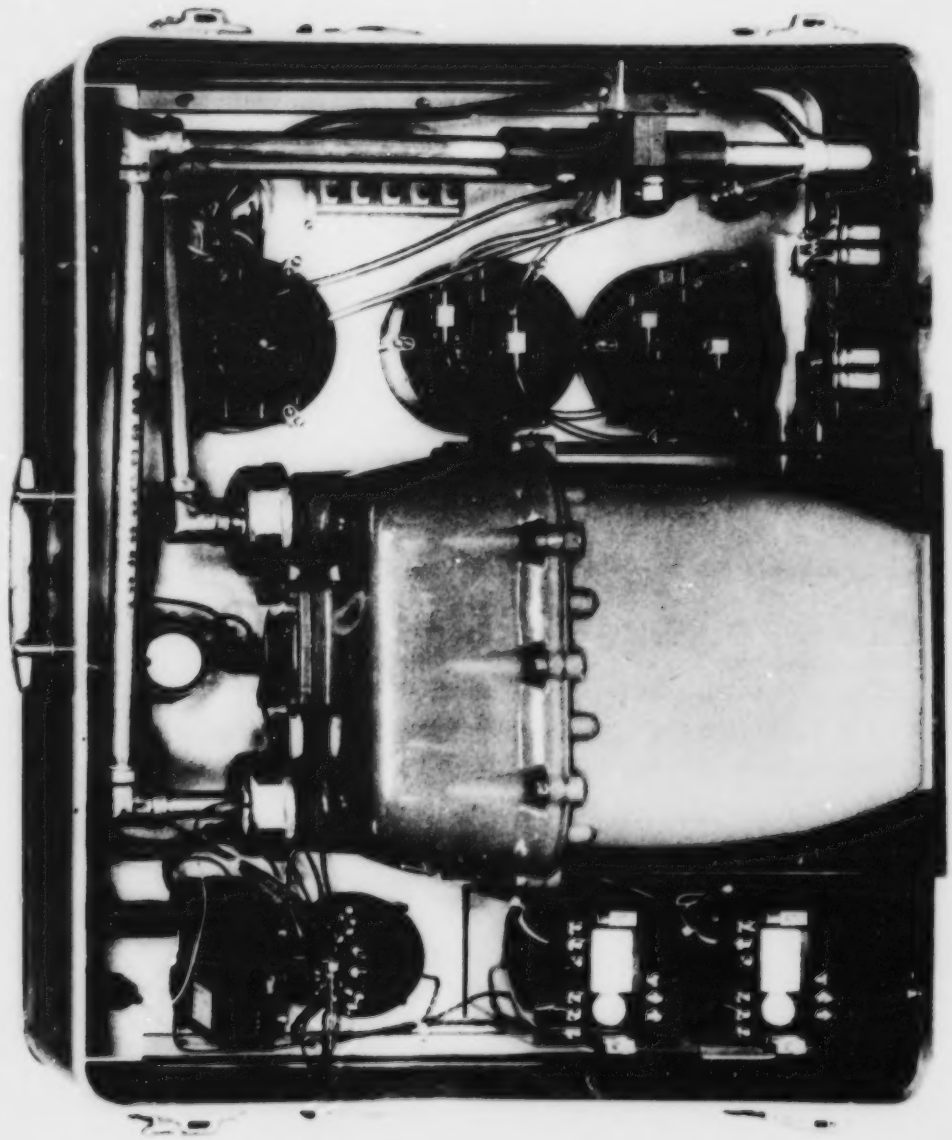


Figure 2-3. Control Unit, Back Cover Removed

contrast to gages which require calibration. However, manometers contain liquid which could spill during shipment or handling of the control unit, or inadvertently be blown into the pressure sampling lines. For these reasons Magnehelic gages were used.

Umbilical Line Connections

The umbilical line between the control unit, oven, and probe makes the following connections with the control unit:

- Multi-point connector with a.c. power leads to oven, fan, and probe;
- Five dual-pin thermocouple connectors for the stack, probe, oven, and impinger thermocouples;
- Two Swagelok connectors for the pitot tube.

The umbilical line also connects to the vacuum pump. The outlet of the pump is connected to the "inlet" fitting located on the Control Unit. The sample gas then passes through the gas and orifice meter in the manner of the typical Method 5 sampling train.

A quick-disconnect fitting is provided at the sample "exhaust" outlet. A length of tubing can be connected at this point for leading noxious sample gases away from the control unit area.

Power Inlet Connectors

Two power connectors are shown. One provides the power for operating all equipment located in the control unit and the fan. The other connector provides power for the probe and oven heaters. The vacuum pump has a separate power line and power switch.

The power lines were divided in this fashion to assure that the system could be connected to several separately fused lines to obtain the necessary three kilowatts of power.

The control unit has a removable back cover. This feature provides ease of access for assembly or repairs, and for setting the orifice size on the three-position orifice meter (right side, Figure 2-3). Three orifices are used for high accuracy measurements over the following flow ranges:

- 0.5-1.9 cfm
- 1.4-4 cfm
- 2.2-6 cfm

The pressure drop for each of the above ranges is typically 0.5 to 4 inches of water at the specified flow rates.

2.2 OVEN

The oven contains the cyclone and filter and supports the probe and impinger train (Figures 2-1, 2-4, 2-5, 2-6). It is a sturdy, double-walled box with two inches of fiberglass insulation. When the oven interior is at 500°F, the exterior is safe to touch.

The maximum power dissipation of the single sheathed heating element is 1200 watts. This is sufficient to bring the oven up to 500°F in less than fifteen minutes. A circulation fan increases the heat transfer rate to the cyclone separator and filter so that these too are heated within the fifteen minute warm-up period. The fan can also hasten cooldown when the heater is off and oven door is left open.

A cyclone separator is used when the sample stream contains particles larger than 3.5 microns in diameter. The filter attaches to the cyclone or directly to the end of the sampling probe in the event the cyclone is not used. Both the filter and cyclone are constructed of stainless steel. The interior of the filter housing is coated with teflon to prevent the filter from sticking to the housing. The filter has a standard 142 mm diameter which can be purchased ready-cut from several filter manufacturers.

While the oven can easily be heated to 500°F, it is intended that the maximum temperature be limited to 450°F. This is to assure a long life for the silicone rubber gaskets on the door jamb.

A rack is provided beneath the installed filter for placing a second filter. The second filter is thus preheated and ready for quick replacement of the first filter if the latter becomes excessively clogged.

2.3 PROBE

The probe can be mounted on the oven in any of the following configurations:

- Probe body horizontal (usual position)
- Probe body vertical (Figure 2-7)
- Probe tip assembly rotatable through 360° (Figure 2-8)

With this flexibility in probe orientation, nearly any sampling situation can be accommodated.

Figure 2-4. Oven with Carrying Case

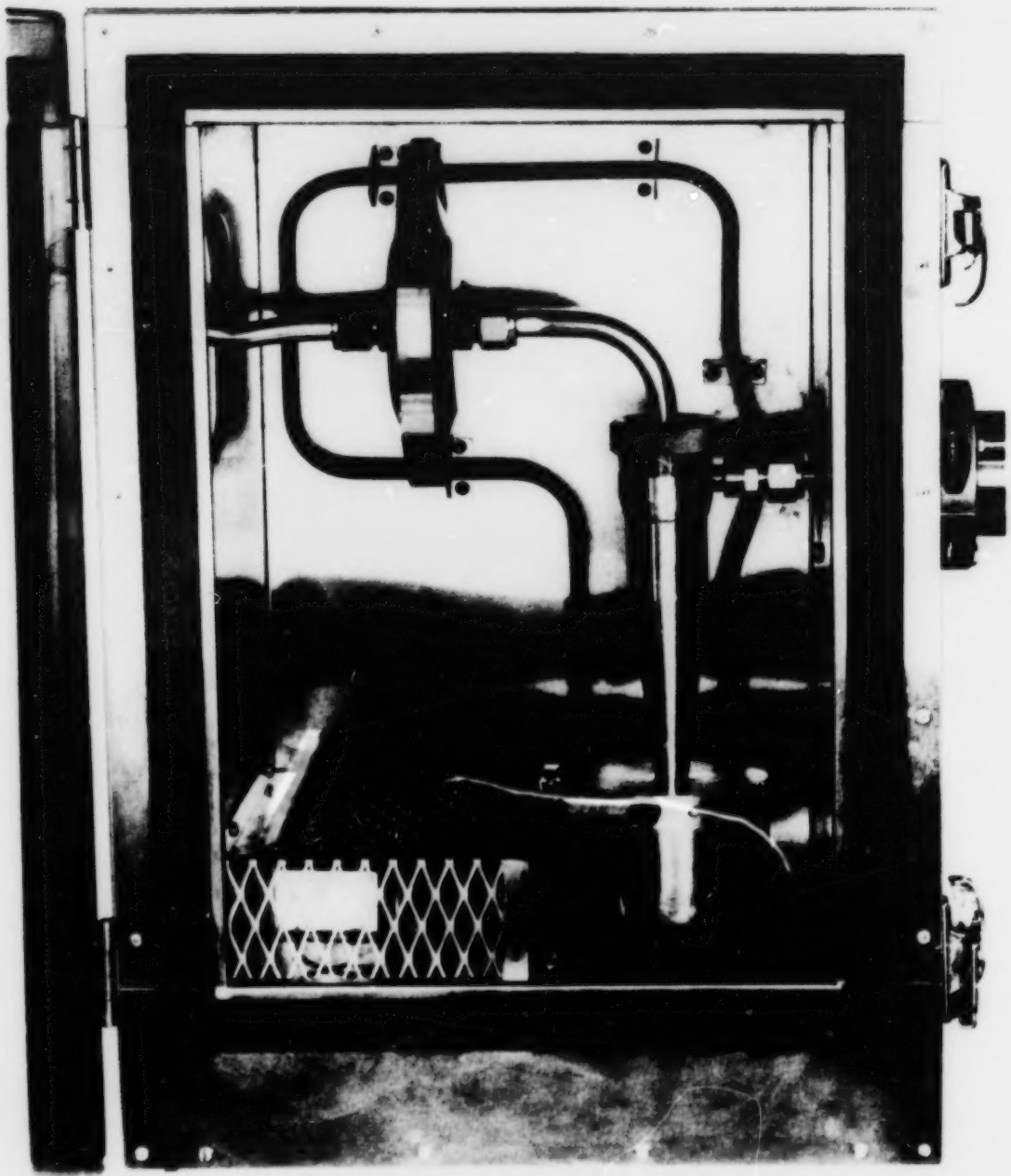


Figure 2-5. Oven with Cyclone Separator and Filter in Position for Use

Figure 2-6. Details of Filter Housing and Cyclone Separator

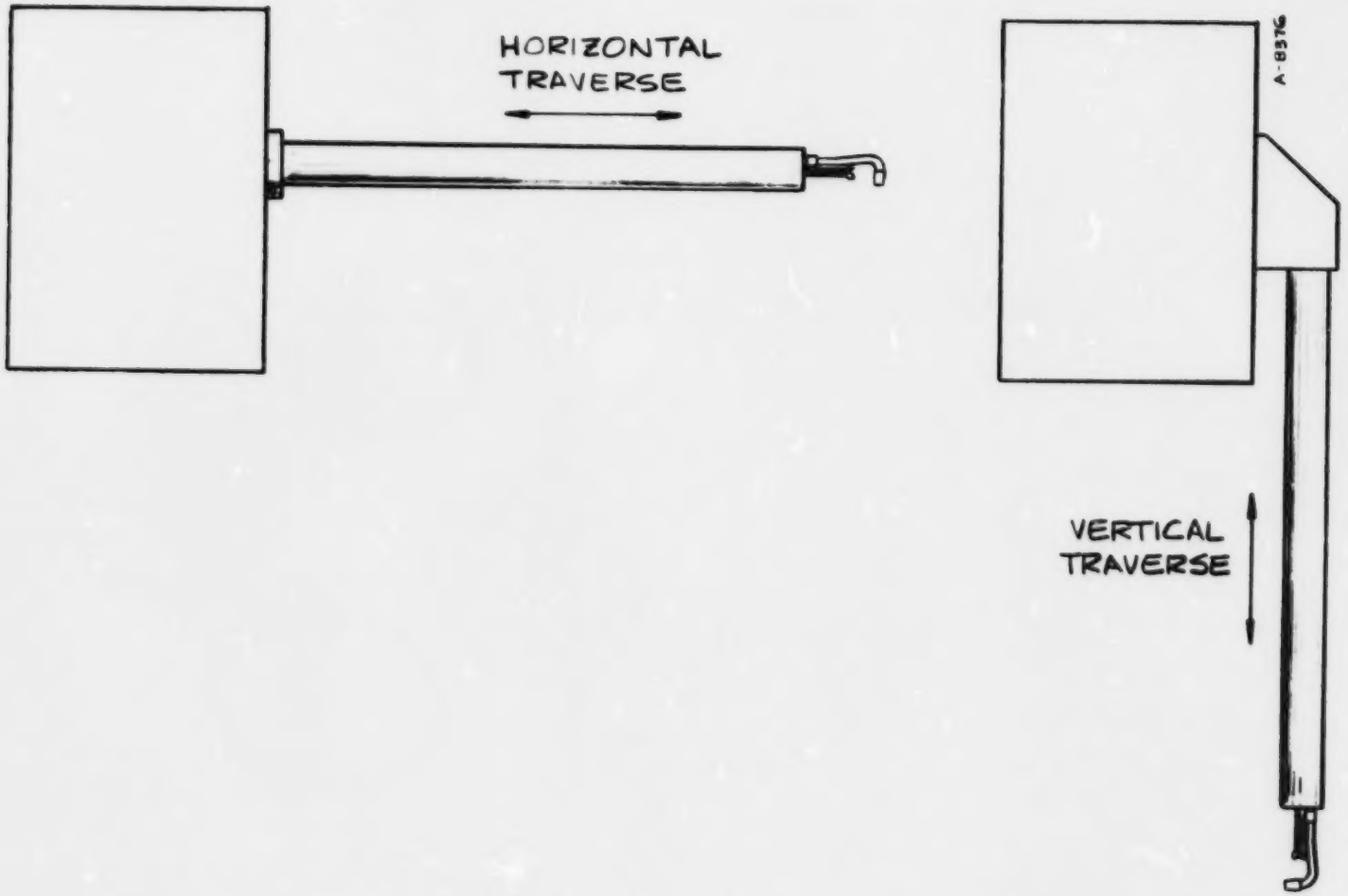
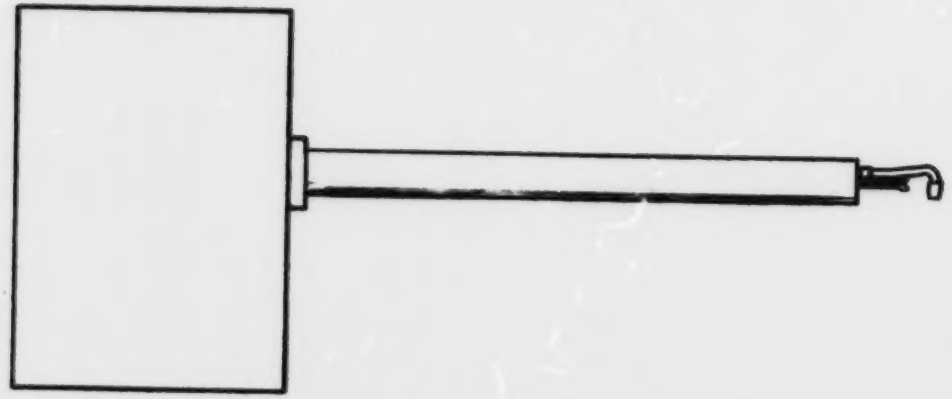


Figure 2-7. Probe Mounting for Vertical or Horizontal Traverses



PROBE ROTATABLE
THROUGH 360°

Figure 2-8. Rotation of Sampling Probe

The principal probe details (Figure 2-9) are as follows:

- Stainless steel sampling tube
- Fiberglass insulated strip heater
- Round probe body
- Strain relief for all electrical, thermocouple, and pitot line connections
- Interchangeable probe tips with diameters from 1/4 to 3/4 inch.

The round probe body is an important feature not usually found on sampling equipment. Because the body is round, the sampling port can be sealed very easily. A good seal is necessary as part of proper sampling practice and for the safety of nearby personnel.

2.4 IMPINGER TRAIN

The impinger train has several functions listed below in order of importance:

- Cooling the sampled gas to a temperature level safe for the pump and gas meter
- Condensing for the purpose of determining water concentration
- Collection of particulates too fine to be trapped by the filter
- Chemical analysis

The above ranking is not arbitrary. Cooling the sampled gas stream is an essential feature of the impinger train. Moisture concentration must be determined as part of Method 5. The impinger train method is a convenient way for determining moisture concentration. The use of impingers for the collection of very fine particles is presently being argued. Some specialists claim that fine particulates may be formed as chemical precipitates or by condensation in the impinger liquid. Thus the fine particulates collected may not actually be present in the gas stream being sampled.

Chemical analysis by means of impingers has been ranked last because chemical analysis is not always performed concurrently with particulate sampling. The impinger method is useful, however, when searching for trace metals and a wide variety of other chemical compounds. In this case, however, the virtues of isokinetic sampling at high flowrate are not important and a smaller impinger train for the exclusive purpose of chemical analysis is more useful.

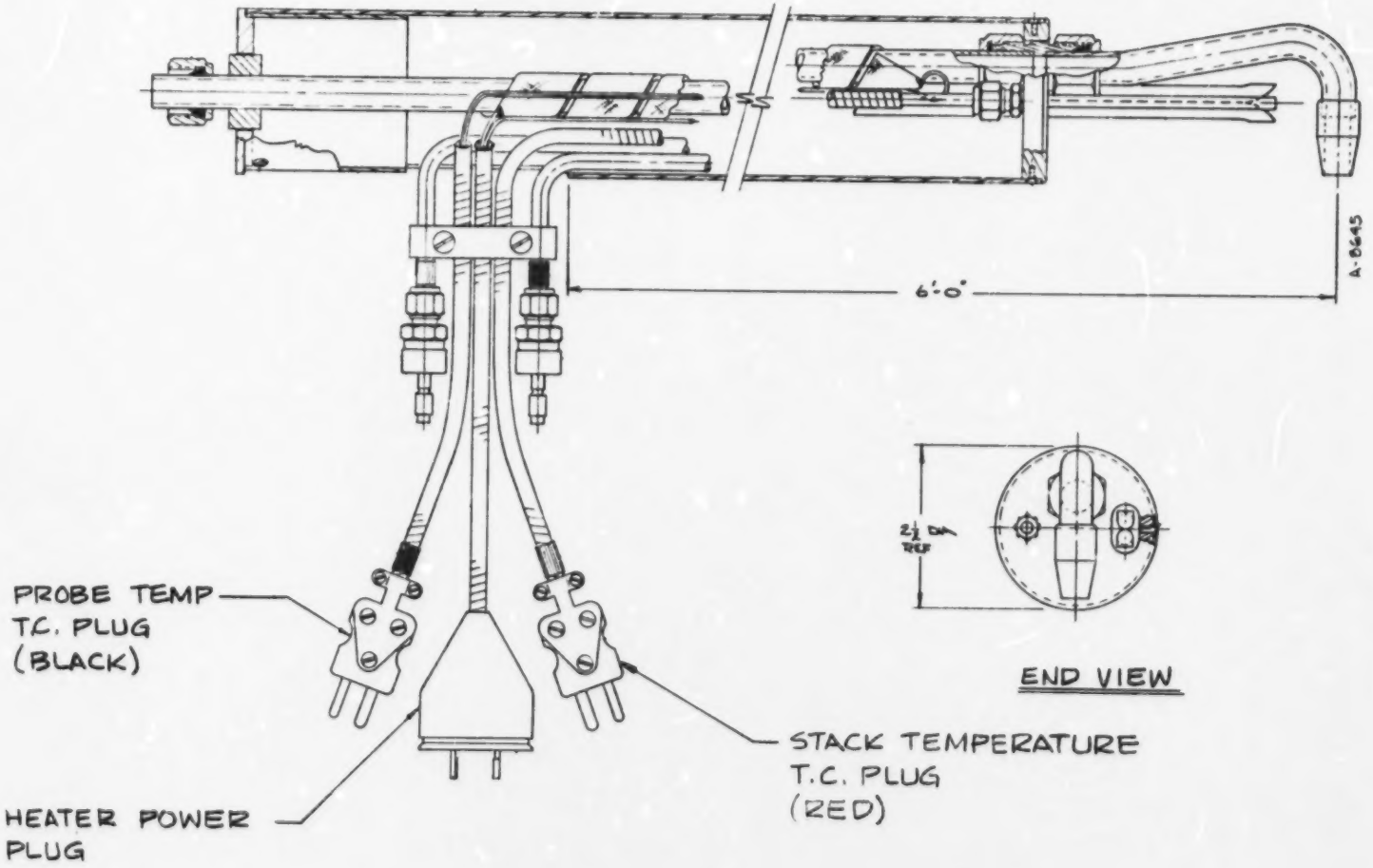


Figure 2-9. Probe Details

The familiar all-glass Smith-Greenberg impingers could not be used above 3/4 cfm because of water carry-over. The glass parts were also too fragile for the rough environment in which stack sampling is performed. The impingers were therefore increased in size, demisters added, and the glass parts were replaced by Lexan plastic or stainless steel parts (Figures 2-10, 2-11). The impingers can be used at flowrates up to 8 cfm.

The interconnections between the impingers are made with stainless steel tubing and Swagelok fittings. This is a rugged, neat method for connecting the impingers as compared to glass tubing and ground-glass spherical joints with clamps.

The impingers are sealed with large diameter caps using "O" rings. Thus the interior of the impinger is completely accessible for flushing or cleaning. The "O" rings make better joints than the more common ground glass joint used on impingers. The "O" rings do not require a layer of grease for sealing and they do not seize as ground glass joints can.

The Lexan plastic is inert to most commonly encountered gases and solvents. In the rare case when Lexan can't be used, the simple cylindrical shape can be produced in glass or teflon.

Other features of the impinger train are the following:

- Impinger rack constructed of PVC plastic
- Thermocouple mounted on cap of last bottle for monitoring outgoing gas temperature
- Stainless steel cap on first impinger to withstand high temperature gas
- Fiberglass carrying case also serves as ice bath
- Carrying case accommodates impingers, rack, and a 25-foot umbilical line
- Impinger train is separable from the oven.

The feature of being able to separate the impinger train from the oven is useful because not all sampling situations involve high temperature gas streams.

2.5 VACUUM PUMP

A vane-type vacuum pump, Gast Model 1022, is used. This pump has a 3/4 h.p. motor, flowrate of 10 cfm at 0 in. Hg, and weighs 59 lbs. including all fittings (Figure 2-12). The features of this pump are as follows:

- Smooth, pulse-free flow
- High vacuum capacity

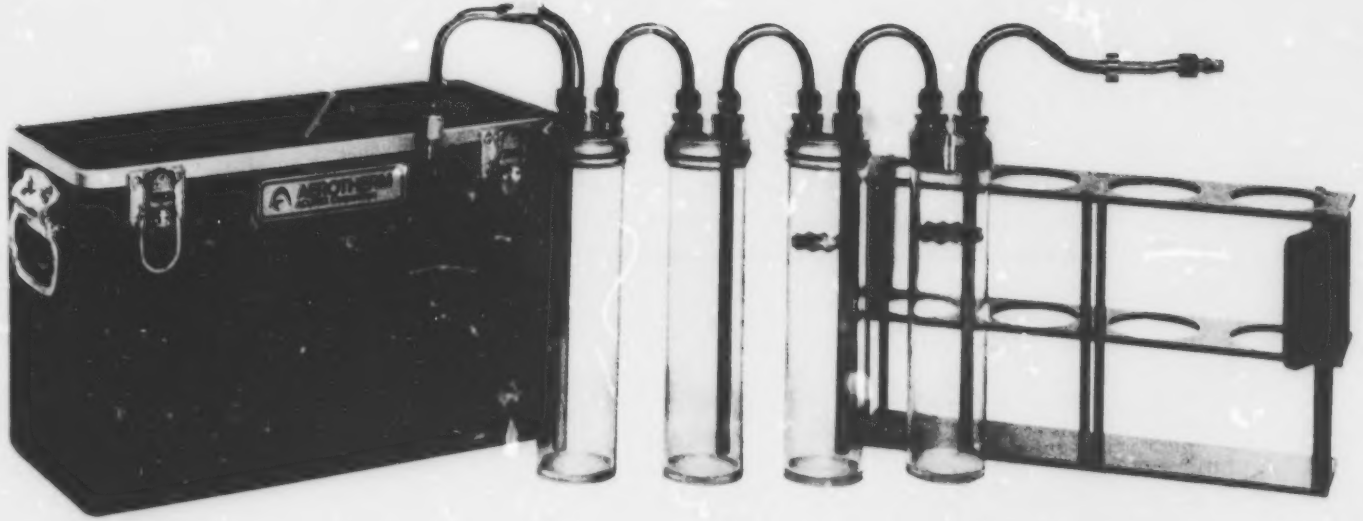


Figure 2-10. Lexan Impingers with Combination Ice Bath/Carrying Case

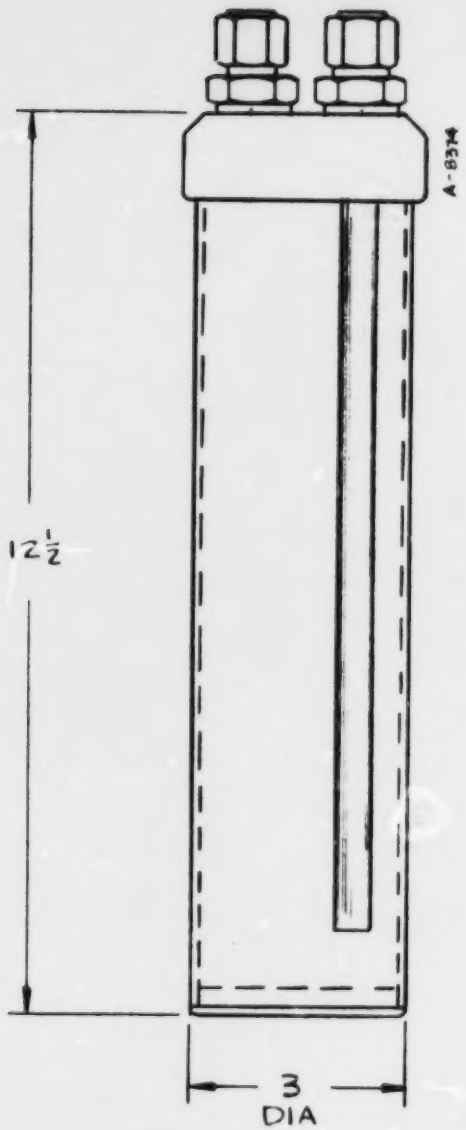


Figure 2-11. Lexan Impinger Dimensions

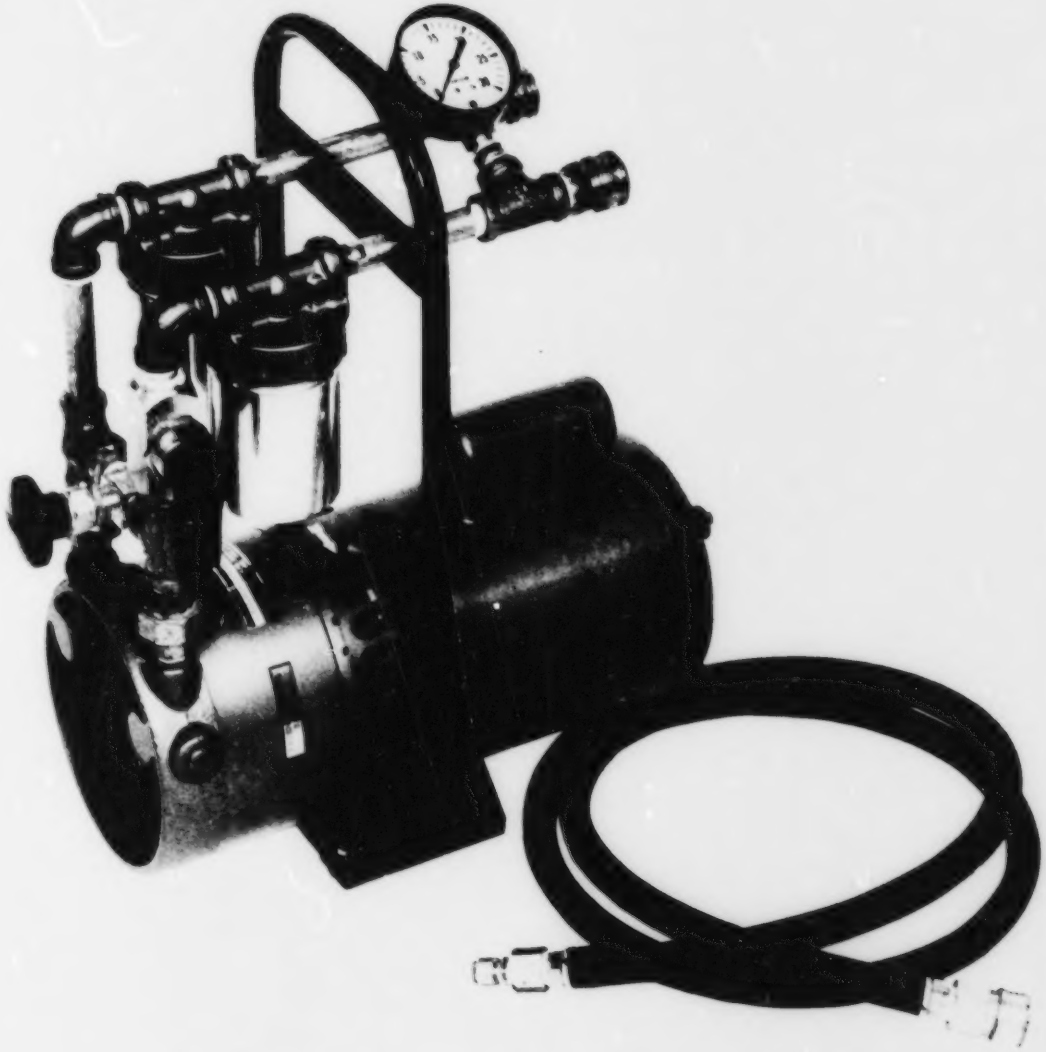


Figure 2-12. Vacuum Pump Assembly

- Self-lubricating carbon vanes
- Special shaft seal
- Coarse and fine flow control valves located on pump
- Carrying handle
- Operates in open air for good cooling
- Unbreakable metal filter and muffler jars
- Vacuum gage to indicate filter condition
- Quick disconnect fittings.

The pump is relatively heavy compared to the lifting capacity of an individual. However, the pump is quite compact and the carrying handle makes its weight manageable. We explored ways for lightening the vaccum pump, including the following:

- Use diaphragm pump
- Have special pump head fabricated from a lightweight alloy
- Use smaller pump operated at higher rpm
- Substitute a high performance induction or universal motor for the standard motor.

A Thomas Model 2727BA39 diaphragm type vacuum pump was evaluated. This pump has two diaphragms, a flowrate of 7 cfm at 0 in. Hg, and weighs 27 pounds. The low weight, as compared to a vane pump, is mostly the result of using lightweight die castings for the pump head.

The diaphragm pump was not satisfactory because of its pulsating flow. It is possible that a surge tank could have been used to reduce the magnitude of the pulsations. However, the additional weight of a surge tank would negate the advantage of low weight in the pump itself.

At one point the leak-free characteristic of the diaphragm pump was considered a strong point. The seals on a vane pump were reworked, however, resulting in a negligible leak rate.

The possibility of a special lightweight pump was also considered. This was not a practical approach because the pump manufacturer (Gast, Inc.) had no interest in producing small quantities, i.e., less than 1,000 units, of a special pump. The same response resulted when we asked for a corrosion-resistant stainless steel pump.

The last two possibilities for reducing pump weight remain practical. As much as 15 lbs. could be saved by operating a small pump at high rpm using

a high performance induction motor. However, the cost of developing a lightweight pump/motor combination was not justifiable on this program.

One of the major reasons for using a vane pump rather than diaphragm pump is the better flow/weight ratio at high vacuum for the vane pump. Above 7 in. Hg, the vane type pump actually weighs less than a diaphragm pump of the same flow capacity.

2.6 UMBILICAL LINE

The umbilical line provides all power, thermocouple, and pneumatic connections between the probe, oven, and impingers and the Control Unit (Figure 2-1). The significant features of this part are as follows:

- Quick disconnects and plugs at each end
- Strain reliefs to prevent inadvertent opening of connections or wearing of lines
- Smooth, kink-free, waterproof sheath for enclosing all lines
- Mating ends of connectors configured so that umbilical line length may be increased by plugging in additional line.

The basic umbilical line has a length of 25 feet.

2.7 TRAVERSING STAND

The oven with probe attached is supported from a roller-carriage running on a track in the traversing stand (Figure 2-1). Thus the probe can easily be guided across the stack being sampled.

The stand can be erected in two configurations, one for horizontal probe traverses, the other for vertical traverses (Figure 2-13). The height of the stand is adjustable over a distance of 7 feet for horizontal traverses. The stand breaks down into pieces for convenience in shipping.

2.8 COMPARISON OF ACTUAL SAMPLING SYSTEM TO DESIGN OBJECTIVES

The design objectives were to construct a Method 5 type of sampling train having a flow capacity of 5-10 cfm, portability, ruggedness to resist the rigors of shipment, and ease of set-up and handling. The oven and probe were to be heatable to 500°F. The system was to break down into modules weighing no more than 50 lbs.

The sampling train actually constructed samples at a maximum rate of about 6 cfm, limited by the vacuum pump capacity. With a larger vacuum pump,

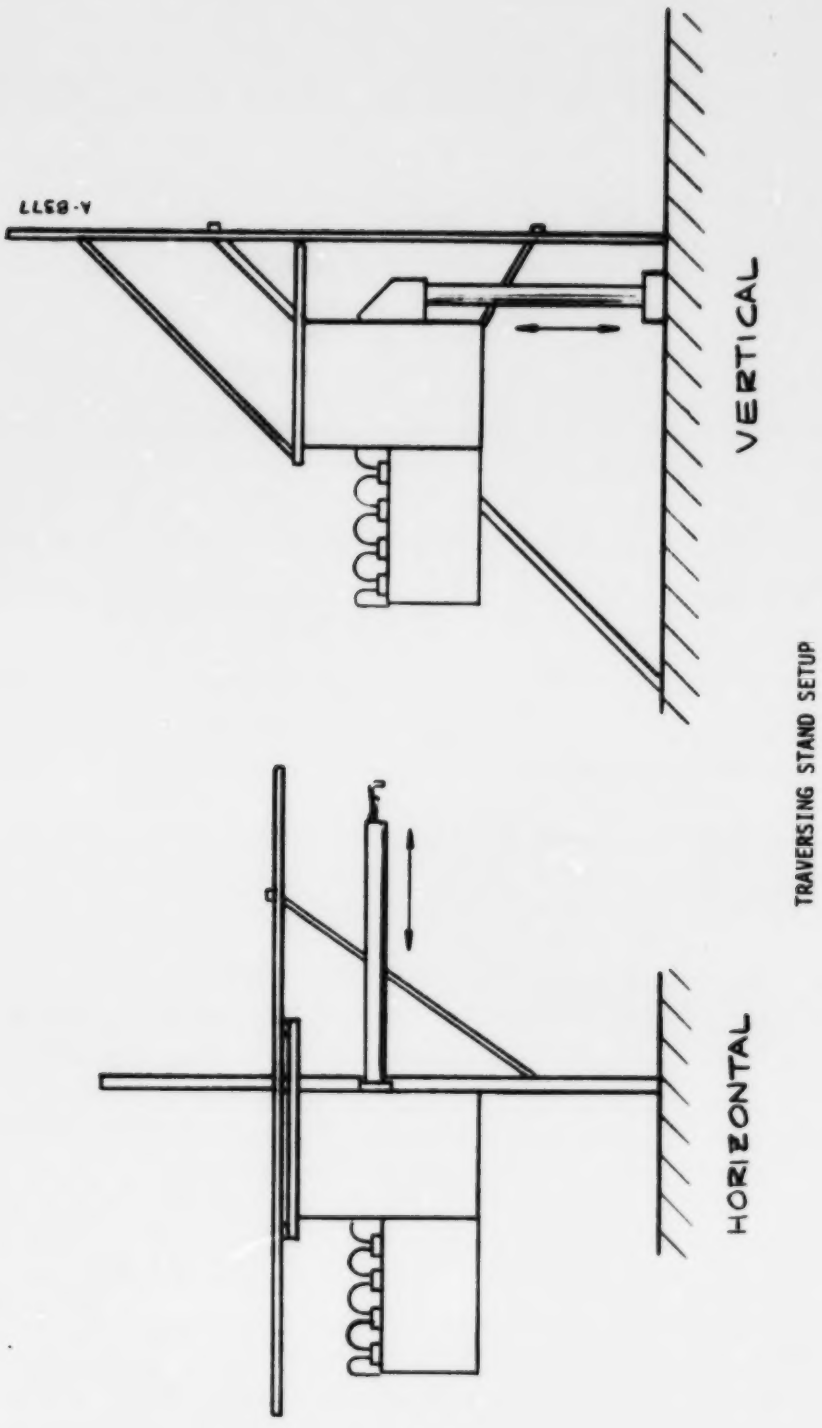


Figure 2-13. Traversing Stand Set Up for Horizontal or Vertical Traverses

the capacity can be increased to 8 cfm when the flow is limited by water carry-over in the impinger train. The oven and probe may be heated to 500°F, although for long life of the oven door gaskets, 450°F is a better limit. The heaviest modules in the system are the control unit, 66 lbs., and the pump, 59 lbs. While these modules are heavier than desired, they are quite manageable because of the handles provided.

Rugged shipping cases are provided for all parts of the system: high impact strength fiberglass for the control unit, oven, impinger train, and vacuum pump; steel reinforced plywood for the probe and traversing stand.

The entire system can be unpacked and set up for use in less than one hour. Heating time for the probe and oven is less than 15 minutes.

SECTION 3

RECOMMENDATIONS FOR FUTURE WORK

The two most useful objectives for future work are weight reduction and simplification of operation. To illustrate, the present high volume sampling system has a weight of 300 lbs. including 90 lbs. of shipping containers. The valve adjustments and computations for establishing isokinetic sampling conditions are repetitive, tedious, and require the abilities of a skilled technician. Fortunately, weight reduction and simplification of operation are complementary objectives.

One of the main contributions to the weight of a stack sampling system is the meter used for measuring total sample flow. A 6 cfm sampler, for example, requires a bulky meter weighing about 20 lbs. The reason for using this type of meter is that it is simple and inexpensive. If the instrumentation is changed so that an electrical signal corresponding to flow rate is produced, then electronic flow integration becomes possible. The gas meter is thus replaceable by an electronics module weighing a few ounces. There are further advantages, however. The sampling system can now be made to automatically maintain isokinetic sampling conditions. Since all parameters are available as electrical signals, e.g. stack temperature, velocity, sampling rate..., it is feasible to automate the recording of data also. (See Table 3-1 for comparison of manual and automated sampling systems.)

The concept for an advanced, automated particulate sampler would not have been very practical two years ago. It was about then that small, versatile computers for process control and low-cost digital displays began to appear on the marketplace.

A sampler based on a digital computer would have these capabilities:

- Continuous, automatic control of sampling rate
- Compensation for stack temperature variations
- Control of probe and oven heaters
- Continuous digital display of all important test parameters
- Data logging on magnetic tape cassette
- Data logging on digital printer

TABLE 3-1

SUMMARY OF SAMPLING SYSTEM CONCEPTS

System Type	Description	Estimated Cost* Dollars
Manual	Data taking and adjustment for isokinetic sampling entirely manual. System is heavy, requires skilled operator. Because of simplicity easy to comprehend its use and maintenance requirements. Currently most common type of sampling system.	2,500-6,000
Semi-automatic	Adjustment for isokinetic sampling automatic, but manual data taking. Simplifies operation of sampler, reduces skill level required of operator and chances for error. Isokinetic conditions and flow regulation determined by simple analog or digital computer. Electronic flow integration. System bulk and weight reduced to half that of manual system. Adaptable to continuous monitoring applications.	4,000-12,000
Automatic	Adjustment for isokinetic sampling and data taking are automatic. Data recorded on tape cassette for rapid data reduction. Cassette interface with computer for data print-out, calculations, or curve plotting, e.g. temperature and velocity profiles. Lightweight system requiring minimum of skill to operate. Adaptable to continuous monitoring applications.	6,000-14,000
Automatic Sampling and Probe Traversing	All the features of the automatic sampler with the additional advantage of automatic probe positioning. A single operator can monitor several units simultaneously. Adaptable to continuous monitoring of large stacks.	7,000-15,000

*Assuming small quantity production, e.g. 10 units

Some of the features of the automated sampling system are considered below (Figure 3-1). First, it should be noted that the operator must initially supply some basic data to the computer, e.g., stack pressure, molecular weight of the sampled gas, and the desired probe and oven operating temperatures. The operator must also select the appropriate sampling nozzle diameter.

The sample flowrate is measured with a turbine flowmeter. This type of flowmeter is usable over a flow range of at least 10:1, has a digital signal corresponding to volumetric flowrate, and is nearly insensitive to gas viscosity. The flowmeter is placed in the oven, together with the cyclone, filter, and motorized control valve. Thus none of these components are affected by condensation of water or other vapors.

A gas-to-air heat exchanger would be used instead of an impinger train for cooling the sample gas. This would eliminate the need for ice and result in a lighter weight cooling system than the impinger train.

The vacuum pump is located downstream from the turbine flowmeter. With this positioning of components, the leakage characteristics of the pump are not critical, assuming the pump can handle the required flowrate and vacuum. Because the leakage characteristics of the pump are not critical, there is an opportunity to reduce the transported weight of the system in a novel way. The pump can be purchased as a piece of plant equipment and left permanently on site.

All of the important test variables are displayed digitally. The operator can thus verify that all conditions are normal. The data can be automatically recorded on a tape cassette. Using a cassette, the data can be fed into a computer, perhaps over a telephone line, for the determination of velocity profiles and particulate concentrations. A digital printer could be used as a back-up of a tape cassette data logger.

Probe traversing can also be done automatically since all that is required is motion along a straight line. A signal indicating probe position would be fed into the system for recording regardless of whether the probe is moved manually or automatically.

The weight of an automated system would be about 140 lbs., assuming the vacuum pump and heavy vacuum line are left at the sampling site. The greatly simplified operation will free the test personnel so that they can make subjective evaluations of sampling conditions, or conduct other measurements, e.g., chemical analyses.

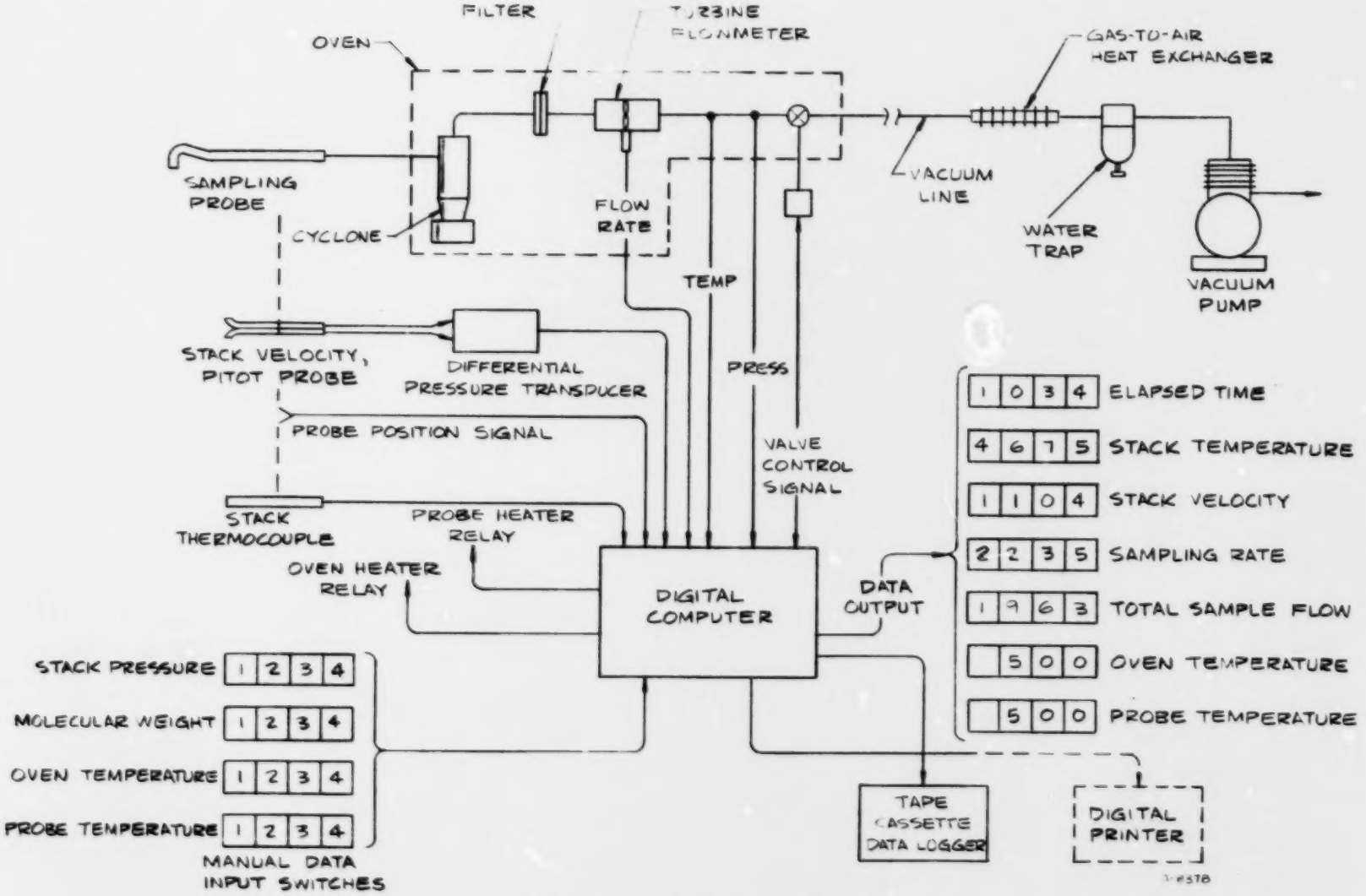


Figure 3-1. Automated Particulate Sampler

An automated, portable particulate sampling system would undoubtedly be useful. A system of this type would have even greater usefulness for continuous monitoring applications where the system is permanently installed on the stack.

APPENDIX A

INSTRUMENTATION FOR STACK SAMPLING

Isokinetic stack sampling with an EPA type of sampling system requires the following measurements:

- Stack temperature
- Temperature at orifice meter
- Stack pressure
- Sample flowrate and cumulative flow
- Stack velocity
- Humidity

The various ways for performing these measurements are indicated in Tables 1-4.

In the future, stack sampling can be expected to become more automated and compact. The measurement methods suitable for the current EPA sampling train will not necessarily be appropriate for the more advanced equipment. For example, it is currently feasible to measure temperatures with glass-stem or bi-metallic thermometers. It is more convenient, however, to measure temperature with thermocouples. All temperatures of concern can then be displayed at a single location, sensor placement is simple in the case of thermocouples, and the temperature is observable as a voltage suitable for recording or as a control signal.

The measurement of flowrate and total flow is another area where improvement is needed. The orifice meters used for measuring flowrate are accurate only over a narrow range of flow conditions. Three separate orifices are necessary, for example, to cover the 0-6 cfm range of the Aerotherm high volume stack sampler. A better way to measure flowrate is with a turbine flowmeter. A single turbine can cover a 10:1 flow range easily. The electrical signal produced by the turbine flowmeter is useful as the input to a controller which automatically maintains isokinetic sampling conditions. The flowmeter signal can also be integrated electronically, thus eliminating the requirement for a heavy, bulky gas meter.

Stack velocity is usually observed with Magnehelic gages or inclined/vertical manometers. The pitot differential pressure displayed by these instruments is indirectly related to the stack velocity. A direct indication of stack velocity would be useful. This can be obtained by measuring differential pressure with a pressure transducer. The pressure signal would then be processed along with stack temperature in an analog or digital computer having stack velocity for the output.

Table 1. Measurement of Temperature

Measuring Device	Application	Range, °F	Precision, °F	Limitations
Glass-stem thermometers				
Mercury-glass thermometer	Temperature of gases and liquids by contact	−38/575	Less than 0.1 to 10	In gases, accuracy affected by radiation
Alcohol-glass thermometer		−100/100		
Pentane-glass thermometer		−200/70		
Jena or quartz mercury-nitrogen thermometers		−38/1,000		
Gas thermometers	Primary Standard	−459/1,000	Less than 0.01	Requires considerable skill to use
Resistance thermometers				
Platinum-resistance thermometer	Precision; remote readings; temperature of fluids or solids by contact	−320/1,800	Less than 0.2 to 5	High cost; accuracy affected by radiation in gases
Nickel-resistance thermometer	Remote readings; temperature by contact	−150/300	0.3	Accuracy affected by radiation in gases
Thermistors		Up to 600	0.1	
Thermocouples				
Pt-Pt-Rh thermocouple	Standard for thermocouples	500/3,000	0.1 to 5	High cost; also, requires expensive measuring device
Chromel-alumel thermocouple	General testing of high temperature; remote rapid readings by direct contact	Up to 2,200	0.1 to 15	Less accurate than above
Iron-constantan thermocouple		Up to 1,500	0.1 to 15	Subject to oxidation
Copper-constantan thermocouple	Same as above, especially suited for low temperature	Up to 700	0.1 to 15	
Chromel-constantan thermocouple				
Beckman thermometers (Metastatic)	For differential temperature in same applications as in glass stem thermometer	5°C difference	0.01°C	Must be set for temperature to be measured
Bimetallic thermometers	For approximate temperature	0/1,000	1 usually much more	Time lag; unsuitable for remote use; unreliable
Pressure-bulb thermometers				
Gas-filled bulb	Remote testing	−200/1,000	2	Caution must be exercised so that installation is correct
Vapor-filled bulb		20/500	2	
Liquid-filled bulb		−50/2,100	2	
Optical pyrometers	For intensity of narrow spectral band of high temperature radiation (remote)	1,500 upward	15	
Radiation pyrometers	For intensity of total high-temperature radiation (remote)	Any range		
Seger cones (fusion pyrometers)	Approximate temperature (within temperature source)	1,000/3,600	50	
Indicating crayons	Approximate temperature (on surface)	125/900	±1%	
Melting and boiling points of materials	Standards	All except extremely high temperature	Extremely precise	For laboratory use only

Table 2. Measurement of Absolute Pressure

Measuring Device	Application	Range	Precision	Limitations
McLeod gauge	Very low absolute pressure	0–0.1 in. Hg	2–5%	Not direct reading; vapors tend to condense out
Pirani gauge				Must be calibrated for gas composition on which used
Thermocouple vacuum gauge				
Absolute-pressure manometer	Moderately low absolute pressure	0–30 in. Hg or above	0.01 in.	Not readily portable
Diaphragm gauge		0.1–20 mm Hg	0.05 mm Hg	Direct reading
Barometer, mercury-manometer type	Atmospheric pressure		0.001–0.01 in.	Not readily portable
Differential manometer and barometer	Moderately low absolute pressure	0–60 in. Hg or above	0.01 in.	Awkward observation; requires two readings
Evaporation liquid temperature	On refrigeration machine and for use during evacuation	Depends on liquid	1%	Liquid must be kept supplied; can be used only where liquid evaporation will not damage system
Pressure transducers – strain gage, capacity, potentiometer, crystal, magnet, and others	Remote reading, responds to rapid changes of pressure	0.05 to 50,000 psi	0.1%	

Table 3. Measurement of Differential Pressures

Measuring Device	Application	Range	Precision	Limitations
Micromanometer	Very low pressure differential	0–6 in. H_2O	0.0005 in. H_2O	Not readily portable; not easy to use with pulsating pressure
Draft gauges	Moderately low pressure differential	0–10 in. H_2O	0.005 in.–0.05 in. H_2O	Must be leveled carefully
Manometer	Medium pressure differential	0–100 in. H_2O or Hg	0.05 in.	Where used with liquid must be compensated for liquid density
Swinging-vane type gauge	Moderately low pressure differential	0–0.5 in. H_2O 0–20 in. H_2O	5%	Generally usable to atmospheric pressure only
Bourdon-tube type	Medium to high pressure differential usually to atmosphere	Any	As high as 0.01 psi or 0.01% of full scale	Subject to damage due to over-pressure shock or pulsation
Pressure transducers – Strain gage, capacity, Potentiometer, crystal, magnet	Remote reading, responds to rapid changes of pressure	0.05 to 50,000 psi	0.1%	

Table 4. Measurement of Humidity

Measuring Device	Application	Range	Precision	Limitations
Wet-bulb thermometer with dry-bulb thermometer (Psychrometer)	Room of building, outside air, air moving in ducts: standard method	0 to 500	0.1 to 1	Should be used in air stream moving 1,000 to 1,500 fpm or correction made. Thermocouple may be used at lower velocities. Difficult to use at sub-freezing temperature.
Dew-point apparatus				
Condensation type	Occasional laboratory work; not widely used	−180 to 200	2	Cumbersome, expensive, difficult to use with precision; unsuitable for remote use
Fog type	Simple wide range method	−100 to + 100	2	Series of readings necessary for determination
Electrical conductivity type	Accurate measurement of dew point; suitable for remote use	0–200	1	Unusable below −20° F and below 15% rh or for any moderate humidity at temperature under 0° F
Hygrometer (for relative humidity)				
Hair hygrometer	For direct relative humidity (rh) in air where motion is slight	0 to 100% rh −40 to 150 F	3% rh	Considerable lag; low sensitivity; adversely affected by temperature above 125° F and rh below 20%; frequent calibration required when used at extremes of range
Hygroscopic material other than hair	Same as above – also for high sensitivity	0 to 100% rh −40 to 150 F	2 to 5% rh	Frequent calibration required when used at extremes of range
Electrical conductivity	For remote use			Requires frequent calibration
Infra-red Radiation	While usable at all temperatures, it is uniquely applicable to extremely low temperatures			Requires the use of very costly equipment
Standard salt	For standards			
Chemical analysis				
Absorption and weighing				Cumbersome process

Note: Tables 1 - 4 are from the article "Significance of Errors in Stack Sampling Measurements" by R. T. Shigehara, W. S. Todd, and W. S. Smith.